Method and application of characterisation of life cycle impact data of construction materials using geographic information systems

Zea Escamilla, Edwin ; Habert, Guillaume

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Method and application of characterization of life cycle impact data of construction materials using geographic information systems

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Abstract

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Methods This methodology was based on the characterization of data and life cycle assessment (LCA) using geographic information systems (GIS), which has been proposed as an effective alternative for this purpose. The data were characterized at three levels: global, represented by different production efficiency of materials; regional, represented by the type of electricity mix used in the production and the national transport at the country level; and local, represented by external factors, such as seismic and wind risk zones at the city level. A comparative LCA was used as case study to test the methodology. The functional unit for the LCA was defined as an 18 m^2 core shelter unit consisting of structural elements only. The bill of materials for five designs were calculated, each using a distinctive construction material: bamboo, brick, concrete hollow block, ferro-cement panels, and soil-stabilised bricks. The contributions' variability and uncertainty analysis were used to validate the consistency of the results. The effect of the external constraints (earthquakes and wind) were analysed, and the environmental impact over the whole life cycle was assessed. Five house designs were calculated in 25 countries based on three levels of production efficiency and three transport distance ranges for each country.

Results and discussion The results of the bamboo, concrete hollow block and ferro-cement houses overlapped and changed depending on the construction materials' transport distance. Therefore, the level of impact of an average bamboo house can also be achieved by a high-performance block or ferro-cement house. The results showed that in most cases, the buildings with high technical performance can be achieved with low environmental impacts.

Conclusions The use of GIS enables the development of characterized LCIA data for construction materials and buildings with a high degree of consistency. Moreover, the proposed approach was able to accurately represent the range of production practices used outside Europe. Finally, the use of the proposed methodology allows for

the assessment of building in the early stages of design when uncertainty is at its highest, thereby identifying the improvement potential of each design and recognising the structural needs in specific locations.

Keywords: LCA, GIS, regionalisation, buildings, transport distance, earthquake, wind, Python

1. Introduction

Over the past few decades, life cycle assessment (LCA) was developed and established as the main methodology to quantitatively assess the environmental impacts of goods and processes throughout their entire lifespan. The models used in an LCA propose a cause-effect relationship between the environment and human activities to highlight their impacts and consequences (Hellweg and Mila i Canals 2014). LCA has been used to assess the environmental performance of buildings and construction materials for more than 20 years (Fava 2006); however, its application has been predominately limited to Europe. The application of LCA faces many challenges including, impact allocations (Reap et al. 2008a; Reap et al. 2008b); end-of-life scenarios (Dubreuil et al. 2010; Kim et al. 1997); system's boundaries (Frischknecht 2010). More importantly, the availability and quality of globally referenced data hinders the application of LCAs (Gomes et al. 2013; Langevin et al. 2010; Mutel and Hellweg 2009).

LCA can be used to identify the most promising strategies for improving the environmental performance of products and services throughout their whole life cycle; this assessment can offer a better understanding of the impacts of human activities on the environment (Hellweg and Mila i Canals 2014). However, human activities and their impacts on the environment can be geographically separated during the supply chain and/or during the life cycle of the product. The use of site-dependant life-cycle impact assessment (LCIA) has been proposed as an approach to reduce the uncertainties associated with the geographical location and regionalisation of life cycle impacts (Nansai et al. 2005; Potting 2000). Many of these methods are focused on developed countries, and the lack of a standardized regionalisation approach of the LCA is evident (Mutel 2012).

To fulfil this need in a cost effective manner, the use of geographic information systems (GIS) has been proposed (Gasol et al. 2011; Liu et al. 2014; Mutel et al. 2011). GIS was developed to capture, manage, analyse and display all types of geographically referenced information. The primary use of GIS is to graphically represent and understand data (Liu et al. 2014). GIS has been widely used to conduct assessments on environmental impacts (Fallahi et al. 2008; Jankowski 2009) and biodiversity (Gontier et al. 2006). Furthermore, GIS has been used as a decision-making tool in several fields (Ramsey 2009), such as forestry, greenhouse gas emissions, risk assessment, land use, urban development and sustainability (Graymore et al. 2009; Höhn et al. 2014; Javadian et al. 2011; Tang et al. 2011; Yousefi-Sahzabi et al. 2011; Zeilhofer and Topanotti 2008; Zhang et al. 2012).

GIS technologies may permit location matching in LCA models when a direct correspondence between the inventory datasets and evaluation methods is unavailable (Mutel and Hellweg 2009). This coupling produces finer resolution results while recognising that production efficiency and its environmental impact have variability that is intrinsically connected to the geographical context (Dresen and Jandewerth 2012; Mutel et al. 2011). In the specific case of the LCAs of buildings, geographically linked factors play a very important role, but they are difficult to address in a LCA. Factors such as land use, seismic risk zones, and the transport distances of materials are quite straightforward when using GIS technology (Geyer et al. 2010), but they are quite complex to represent in a LCA. Transport is of great interest due to the high levels of associated greenhouse gas emissions and the challenge of correctly estimating transport distances, particularly in an LCA (Fries and Hellweg 2014). These distances are related to the suppliers and producers of construction materials, which in many cases are unknown at the moment of the assessment. This uncertainty is increased when considering the role that global international trading plays on modern economies. Moreover, it highlights the need to compare environmental impacts between locations of resource extraction and use through the regionalisation of LCA data and methods (Hellweg and Mila i Canals 2014).

Furthermore, even if the methods and impacts are regionalised, the data of bio-based products in the current databases are incomplete due to the large variability in agricultural production levels in various regions (Azapagic et al. 2011; Hoxha et al. 2014). This is also true for bio-based and alternative construction materials outside Europe, in which variations in production practices and electricity mixes can dramatically influence the results of a LCA (Zea Escamilla and Habert 2014). To address this problem, the contribution to variance (CTV) has been proposed as a global sensitivity test for LCAs (Azapagic et al. 2011; Hoxha et al. 2014). The CTV expresses the contribution of each parameter to the overall variance in the LCA results as a proportional ratio between the variation of inputs and results. This parameter is important for improving data quality, allowing a practitioner to focus on the main contributors to the environmental impact (Mutel et al. 2013). Moreover, this approach can be used as a basis to calculate the uncertainties related to construction materials in a building (Hoxha et al. 2014), thereby improving the overall consistency of the LCA results. In the case of alternative construction materials: (i) electricity mix, (ii) production efficiency and (iii) transport have been identified as main contributors to the variation and uncertainty of LCA results (Balzarini 2013; Zea Escamilla and Habert 2013).

Using LCA for buildings is unique due to the intrinsic diversity of the data on these types of assessments. Furthermore, it should be conducted at early design stages when it is still possible to make substantial changes to the design (Hellweg and Mila i Canals 2014). This comes at the cost of higher uncertainties regarding the construction materials to be used; their production efficiency; and transportation. The complexity of this setup is increased if the LCA is conducted for regions outside the European context where only limited LCA data is available. This poses a challenge for organizations, working on reconstruction and housing projects in those regions which try to use LCA as a decision making support tool. Under the current conditions the development of LCA data of construction materials and buildings requires a major financial and human talent investment. Nevertheless, these data is necessary to produce insights into the selection of construction materials. Thus, it is necessary to make compromises between the results' precision and the resources available in terms of LCA data, time, and budget.

This study aims to develop a methodology for the LCA of buildings outside the European context by characterizing the LCA data of alternative construction materials with the use of a geographic information system.

2. Methods

This methodology proposes that the LCA of buildings can include the local diversity of production practices by integrating LCA data and geo-referenced data in a GIS. To achieve this goal, the proposed methodology considers three levels of geo-referenced data: (i) global, (ii) regional, and (iii) local, as seen in **figure 1**.

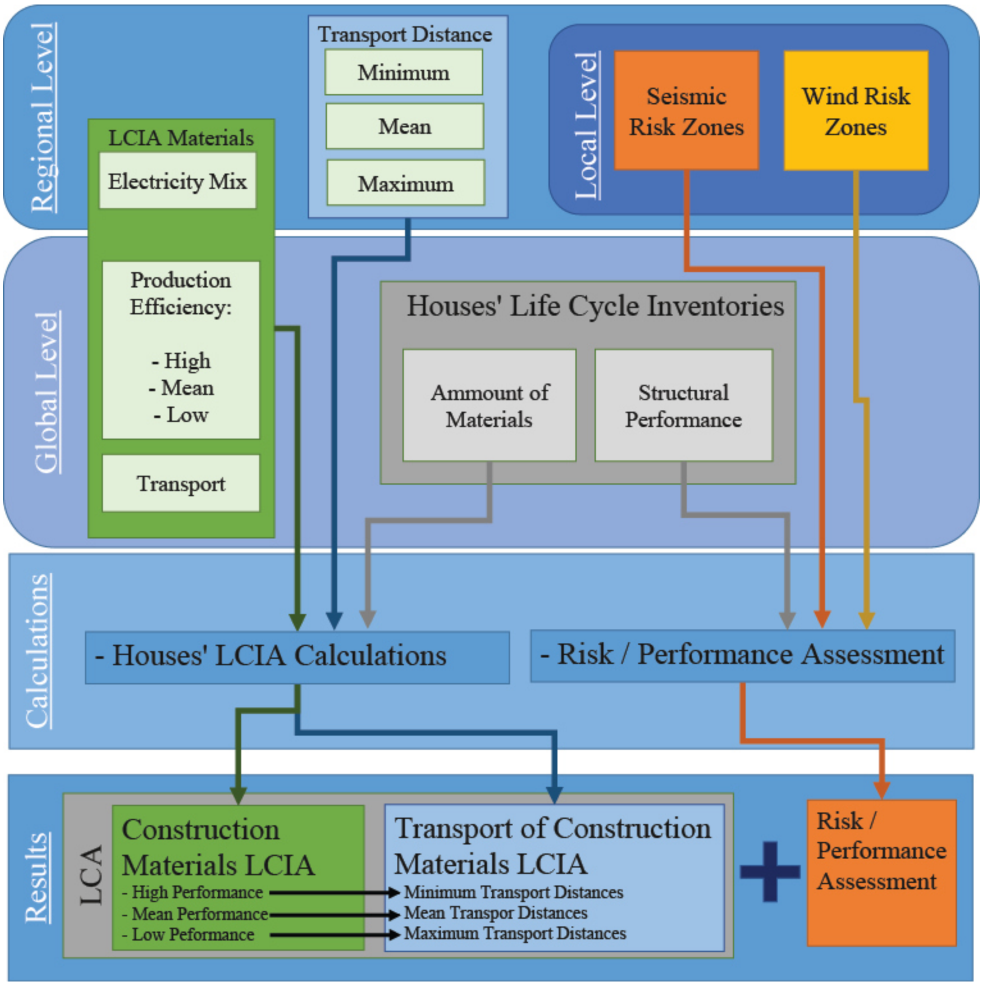

Figure1. Conceptual framework

The global level represents data that can be considered valid worldwide, such as the amounts of material per functional unit and the production efficiency of construction materials. It can be argued that the amount of construction materials needed, to produce a wall for instance, will not drastically vary from one location to another. Furthermore, the production efficiency of construction materials will vary within a range of values (Balzarini 2013; Zea Escamilla and Habert 2013). The regional level contains data that can be linked to a specific country's characteristics, such as electricity mix and transport distances for construction materials. The local level represents data such as seismic and wind risk zones in which the buildings can potentially be constructed. The approach to operationalise the methodology comprises four interconnected steps: (i) characterization of LCA, (ii) calculation of transport distances per country, (iii) LCA of the building, and (iv) identification of seismic and wind risk zones.

2.1. Development of an LCA geo-database

For the characterization process, a geodatabase was created using the software ArcCatalog10.2 (ESRI 2014). The database contained two types of information. The first type was the geo-referenced data of approximately 230 countries and 2000 cities (ESRI 2014), with their respective seismic risks (Giardini et al. 1999) and wind zones. The second type was the LCIAs for the production of: (i) electricity per country (SCLCI 2011); (ii) construction materials considering low, mean, and high production efficiency (Balzarini 2013; Zea Escamilla and Habert 2014). Furthermore, bill of materials of house designs. The LCIAs were calculated using the database EcoInvent 2.7 (Frischknecht and Rebitzer 2005); the software SIMApro v7.3 (Pre-Consultants 2012) and the environmental impact was calculated using the evaluation method IMPACT2002+ (Jolliet et al. 2003b). This method considers four impact categories: (i) human health evaluated in terms of DALYs; (ii) ecosystem quality assessed by the potentially disappeared fraction (PDF) over a certain area and during a certain period per kg of emitted substance (PDF.m^2.yr); (iii) climate change assessed with global warming potential (McCarthy 2001) in terms of kg CO_2 equivalents; and (iv) resources evaluated by the product's energy demand in mega joules (MJ). The results were normalized into a single score value by using the following factors implemented on the software SIMApro v7.3 (Frischknecht et al. 2007): (i) human health: 0.0071 DALY; (ii) ecosystem quality: 13,700 PDF.m^2.yr; (iii) climate change: 9,950 kg CO_2; and (iv) resources: 152,000 MJ(Jolliet et al. 2003a).

2.2. Characterization of the LCA data

The LCIA of construction materials was characterized by two main factors: electricity mix and production efficiency (Balzarini 2013; Zea Escamilla and Habert 2014). For the construction materials the electricity mix used was related with the country of study, except for steel which was considered as produced in China. Three levels of production efficiency were considered for the main construction materials. They consider the production process and energy sources used on the production of the materials. This kind of approach is very useful for the present case, where the LCA data is scarce and time and funding are limited. This approach does not produce an exact result but presents a range in which the result can be found. Furthermore, analysing the contribution to the variability (CTV) was used to calculate the result's uncertainty based on the work of by Hocha et al (2014). To calculate the characterized LCIAs, a script was developed using Python 2.7 (Python 2014) and the module ArcPy (ESRI 2014). The script first identified the country and city to be studied, which were defined by the user. With this information, the database is searched to select: (i) the LCIA from specified country electricity mix; (ii) the country area in km^2; and (iii) the seismic and wind zones in which the city is located. Simultaneously, the script loads the bill of materials for each house design. Then the characterized LCIAs are calculated by adding (i) the LCIA from the electricity mix; (ii) the impact from the production of raw materials; and (iii) processing raw materials into the construction materials per mass unit (EQN 1). These calculations are executed for low, mean, and high production efficiencies of each construction material.

$$LCIA_{\mathrm{mat}} = EI_{elec} + EI_{rawmat} + EI_{process} \quad (EQN\ 1)$$

$LCIA_{\mathrm{mat}}$ = LCIA of materials per kg
EI_{elec} = Environmental Impact from electricity production (country specific)
EI_{rawmat} = Environmental Impact from production of raw materials
$EI_{process}$ = Environmental Impact from production of construction materials

Then, the LCIA of the materials per functional unit are calculated by first multiplying the characterized LCIA of each material with the respective amount of material (EQN 2). During this step, the script calculates three scenarios low, mean, and high performances for each construction material per functional unit, and established a triangular probabilistic distribution for these data. The standard deviation of these data is used in combination with CTV to calculate the results' uncertainty as described by Hoxha et al (2014).

$$LCIA_{fu} = EI_{material/kg} * A_{mat} \quad (EQN\ 2)$$

$LCIA_{fu}$ = LCIA of materials per functional unit
$EI_{material/kg}$ = Environmental impact of production 1kg of construction material
A_{mat} = Amount of material in kg

2.3. Calculation of transport distances per country

The calculation of the transport distances of construction materials is highly uncertain and is often arbitrarily assigned. To rationalise this process, the transport distance was related to the size of the country and the type of construction material. A relation between country's area (km^2) and transport distances (km) was estimated based on findings from the literature presented on Table 1.

Table 1 Land area and transport distances from literature

Country	Land Area Km2	Short distance transport (local) Km	Long distance transport (national) Km	References
Belgium	30,278	N/A	300	(Beuthe et al. 2001)
Netherlands	33,893	100	N/A	(Quak 2008)
Switzerland	39,997	N/A	250	(Maggi et al. 2005)
Greece	130,647	32.5	N/A	(Koroneos and Dompros 2007)
Italy	294,140	50	N/A	(Pulselli et al. 2008)
France	640,427	80	N/A	(Nicolas and David 2009)
Turkey	769,632	250	1250	(Ozen and Tuydes-Yaman 2013)
Peru	1’279,996	71	427	(SwissContact 2013)
Indonesia	1’811,569	75	280	(Utama et al. 2012)
Brazil	8’460,415	34	N/A	(Bonilla et al. 2010)

Source: Authors

From this data it is possible to see that no direct relation can be established, but in nine out of ten cases, the transportation distance was below 600 km. Furthermore, for the countries with sizes below one million square kilometres the range of transport was between 45 and 300 km. The longest transport distances from this sample range between 250 and 1250 km. This can be observed in cases of large countries such as Brazil or Colombia where the construction materials are not transported all over the country, but centres of production are geographically located to cover most of the country’s needs. It was also proposed that the relationship between countries’ area and construction materials’ transport distances will follow a logarithmic pattern (EQN 3). This trend applies for countries with areas larger than 8,870 km^2. In cases in which the area was equal or smaller than this value, the minimum transport distance was used for the calculations. Furthermore, particular construction materials or components have longer transport distances than others. For example, bricks are usually transported over much shorter distances than reinforced steel or cement. To acknowledge these differences, three additional transportation ranges were defined: (i) minimum, (ii) mean, and (iii) maximum transport distances (EQN 3) a sample of these calculations is presented on Table 2:

$$TD = n_{min,\ mean,\ max} * Ln(A) - m_{min,\ mean,\ max} \quad (EQN\ 3)$$

TD = Transport distance
$n_{min} = 51.37$
$n_{mean} = 61.05$
$n_{max} = 76.27$
A = Country’s area in km^2
$m_{min} = 448.36$
$m_{mean} = 500.04$
$m_{max} = 621.59$

Table 2 Potential transport distances (sample)

Country ID	Country's Name	Country's Area (km^2)	Minimum transport distance (km)	Mean transport distance (km)	Maximum transport distance (km)
JM	Jamaica	10831	28.9	67.1	90.4
SV	El Salvador	20721	62.2	106.7	140.1
HT	Haiti	27560	76.9	124.2	162.0
DR	Dominican Republic	48320	105.7	158.4	205.0
PA	Panama	74340	127.8	184.7	238.0
CU	Cuba	109820	147.9	208.6	267.9
NI	Nicaragua	119990	152.4	214.0	274.7
GY	Guyana	196849	177.9	244.2	312.6
EC	Ecuador	256369	191.4	260.3	332.8
VE	Venezuela	882050	254.9	335.7	427.5
CO	Colombia	1038700	263.3	345.7	440.0
PE	Peru	1279996	274.1	358.5	456.0
MX	Mexico	1943945	295.5	384.0	488.0
BR	Brazil	8460415	371.1	473.8	600.7
US	USA	9158960	375.1	478.6	606.8

Source: Authors

The minimum transport distance was used for materials that were considered locally produced, such as bricks, concrete hollow blocks and sand. The medium transport distance was used for gravel, and the maximum transport distance was used for bamboo, cement, and steel. However, because the steel market is an international market, an additional transoceanic transport distance (7,000 km) for all countries was added to the national transport distance. It is important to note that this solution is not completely accurate, and a compromise between data availability and accuracy is needed in this regard. Nevertheless, this method provides the first step in rationalising the calculation of transport distances of construction materials during the early stages of building design. After obtaining these values, the LCIAs from the transport of construction materials were calculated (EQN 4). To obtain this value the amount of material in tons was multiplied by the transport distance calculated for the specific country; and by LCIA of transporting 1 tkm of the material:

$$LCIA_{TD} = A_{mat} * TD * EI_{transport} \quad (EQN\ 4)$$

$LCIA_{TD}$ = *LCIA from transport of materials*
A_{mat} = *Amount of material in ton*
TD = Transport distance of construction materials in km
$EI_{transport}$ = *Environmental impact from transport of 1tkm of construction material*

2.4. LCA of the Building

In order to calculate the LCIA of the studied building the script adds all the characterized LCIAs from construction materials and their transport. This can be easily done due to the fact that all the LCIAs had been normalized into single score values as described in section 2.2. This procedure calculates three levels of performance by combining the results from the high, mean, and low production efficiencies with the minimum, mean, and maximum transport distances respectively.

Then the process contribution to the environmental impact (PC_{EI}) is calculated in form of a proportional ratio between the total environmental impact and the impact of each material per functional unit (EQN 5). Furthermore, the CTV is calculated based on the proportional ration between variation of inputs and the consequent variation of the results (EQN 6).

$$PC_{EI} = (LCIA_{fu,\ TD} / LCIA_{build}) * 100 \ (EQN\ 5)$$

PC_{EI} = Process contribution to environmental impact
$LCIA_{build}$ = LCIA per functional unit
$LCIA_{fu}$ = LCIA of materials per functional unit
$LCIA_{TD}$ = LCIA from transport of materials

$$CTV = (\Delta LCIA_{FU,TD} / \Delta LCIA_{build}) * 100 \ (EQN\ 6)$$

CTV = Contribution to variance
$\Delta LCIA_{FU}$ = Difference between high and low performance levels
$\Delta LCIA_{TD}$ = Difference maximum and minimum transport distances
$\Delta LCIA_{build}$ = Difference between high and low performance levels

2.5. Identification of seismic and wind risk zones

The final step in the calculations is to identify the seismic risk and wind zones in which the studied city was located. This step has a two folded purpose, on the one hand the identification of risk zones at early stages of design allow decision makers to understand better the structural requirements on the zone. On the other hand, it allows to determine whether the studied house design can withstand the external load (earthquake and wind) at the proposed location. Thereby allowing a better comparison between constructive systems.

The identification of risk zones was achieved by using spatial analysis tools in the ArcPy (ESRI 2014) module and the geo-information from the database. Based on this information, an external environmental constraint factor was defined for each location. This factor indicated what the structural demand would be on the location. This factor was compared with the structural performance of the studied building, to calculate the building’s structural performance. If the factor was equal to the performance of the house, then the structure was considered to perform appropriately for the external constraints (earthquakes and wind). If the factor was larger than the performance, then the structure would be at risk of collapsing under the external loads. This condition would require a revision of the structural design or the selection of an alternative design. Finally, if the factor was smaller than the performance, then the building would be able to withstand the external loads but would be over-performing.

2.6. Application

To test the consistency of the proposed methodology a case study was proposed. The case study was a comparative LCA in which the environmental impact of five different construction materials on a singular house design was assessed at twenty locations. For this case the selected locations were concentrated in the American continent and are listed on Table 2. This selection is intended to cover a wide range of country's areas and electricity mixes. Furthermore, all the construction materials are available on the selected countries. The main aim of the case study was to prove the ability of the proposed methodology to characterize LCIA data on regions outside of the European context. The functional unit for the LCA was defined as an 18 m^2 core shelter unit considering only the structural elements. The bill of materials for the five construction material options were calculated and are presented on Table 3. Each option had distinctive construction material: bamboo, brick, concrete hollow block, ferro-cement panels, or soil stabilised bricks. These designs are considered "core shelters" that are generally built during reconstruction projects after disasters (IFRC 2013) or in social housing programs. This type of design was useful for this research due to its simplicity and its global character. The use phase of the buildings was not considered due to the fact that the energy demand from this kind of buildings is independent from the type of construction materials they are built with. Moreover, the selected locations have no seasons, and therefore no heating demand is required.

Table 3 life cycle inventories of construction materials used in five house designs

Materials	**Block House**	**Bamboo House**	**Brick House**	**Ferro-cement House**	**SoilCement House**
Bamboo pole (kg)		160.0			
Flattened Bamboo (kg)		397.8			
Brick (kg)			5,307.0		
Concrete block (kg)	3,816.0	120.0			
Ferro-cement panel (kg)				3,002.7	
Soil stabilized brick (kg)					5,605.1
Reinforcing steel (kg)	1,604.4	524.9	893.8	798.1	690.2
Concrete (kg)	2,878.3	8,800.0	2,878.3	2,878.3	6,397.7

Source: Authors

3. Results & Discussion

The results for the case study considering the environmental impact of the construction materials at different transport distances are shown in figure 2**,** the brick houses had the highest impacts and were excluded from the results to improve the readability. The three levels of performance were represented by bands, in which the lower boundary represent the highest performance achievable at the given average transport distance and upper boundary represents the lowest performance.

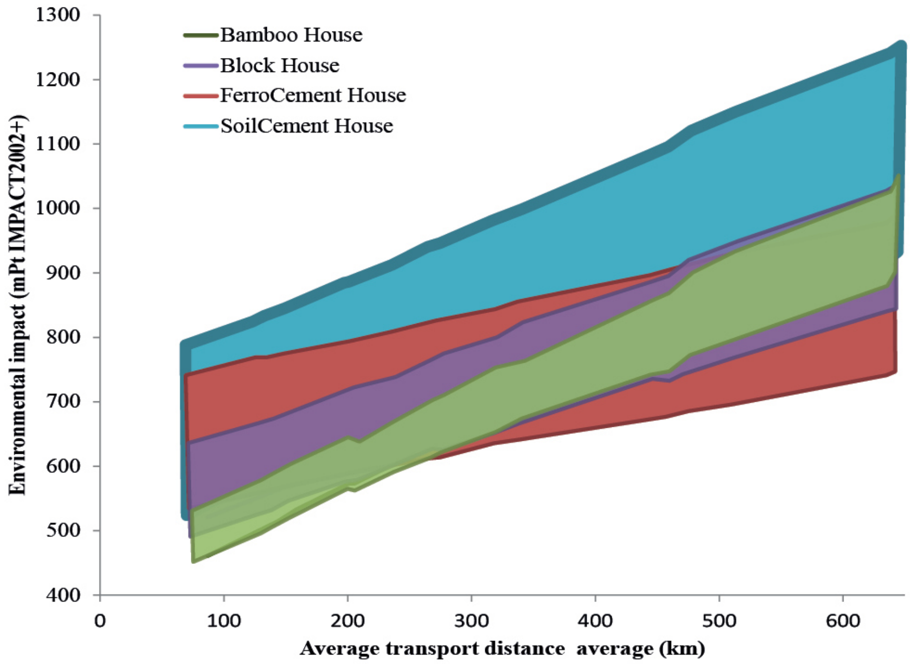

Figure 2. Environmental impact at diverse transport distances

The separation between these two boundaries represent the variability of the results and all the possible combinations of LCIA of construction material and transport might occur within this range. From this figure it is possible to observe that in cases with short transport distances, the variability of the results is smaller than those with long transport distances. For countries with the longest transport distances, the variability of the results was highly influenced by the impact of the transport of materials. From this figure it is possible to see that that the results from different construction materials overlap. This means for instance, that at short transport distances one material might have the best performance but it might not be the best performing at long transport distances.

The results of the bamboo, concrete hollow block and ferro-cement houses were within similar ranges of variability. Therefore, the level of performance from an average bamboo house can be achieved by a high performance block or ferro-cement house even at short distances. Thus, the performance of a given construction technique cannot be directly correlated to the use of specific construction materials but rather to its appreciated use based on the specific location, the efficiency of production and the transportation of the construction materials.

To better understand these results, the contributions of the five construction materials to the environmental impact were calculated and are presented on figure 3.

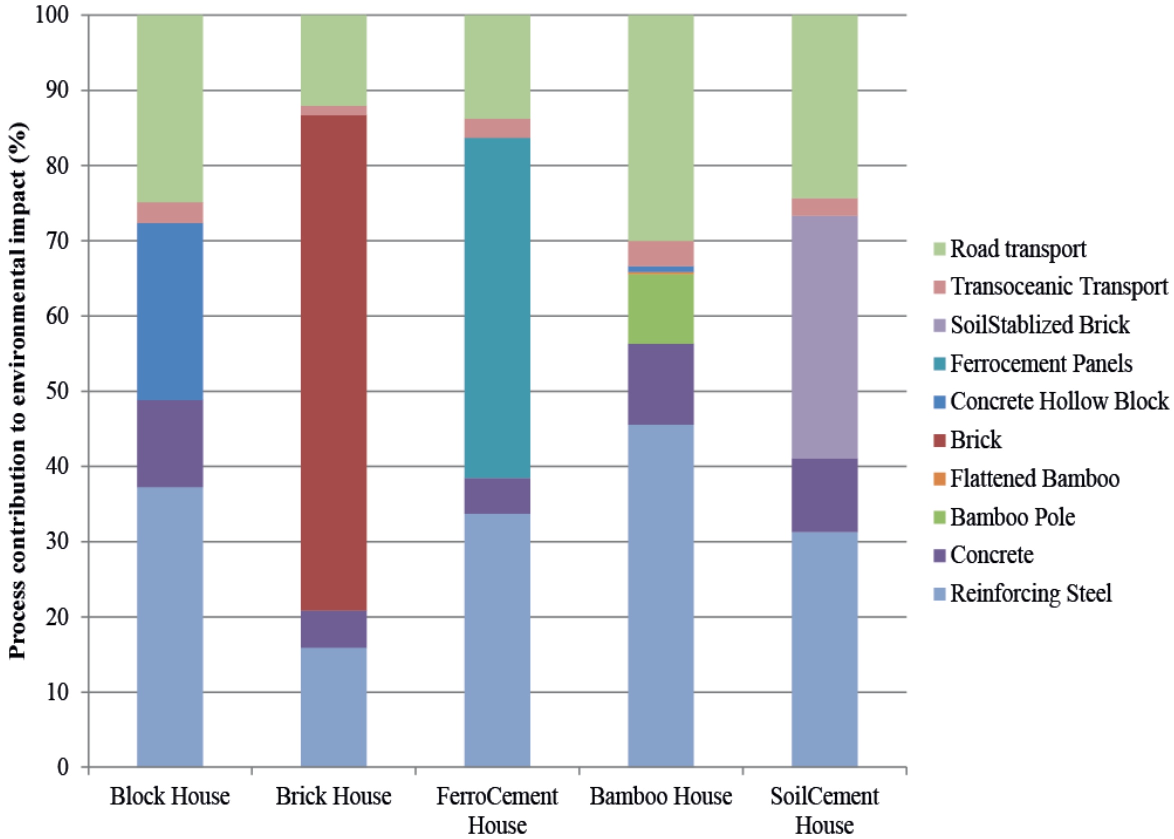

Figure 3. Process contribution to environmental impact

This figure shows the average values for the 25 locations. Thus, representing all the transport distance ranges and electricity mixes. These results show that the construction materials contributed to approximately 70% of the impact, while the transport of those construction materials represented between 15 - 30% of the impact, depending on the construction material. Moreover, in most designs, reinforced steel was the main contributor to the environmental impact (30 - 40%). This shows that special attention must be paid to the possible transport ranges that might be associated with a project (transport distances) and to the external environmental constraints of seismic risk zones and wind loads and thus the need for structural reinforcement.

Further analysis of the different transport distance ranges showed that at distances less than 450 km, the bamboo house had the best performance independent of the electricity mix used. If the high performance level is considered, then this range is reduced to 300 km; if the low performance level is considered, then the ferro-cement house had the best performance at distances greater than 500 km, beyond this distance, the block and ferro-cement houses performed better due to the much shorter transportation distances of the main construction materials. The analysis of the contribution from transport of construction materials was below 10% at short transport distances. At long transport distances the contribution from transport increased up to: 30% for the ferro-cement and brick houses; 45% for the block and soil stabilized houses; and 55% for the bamboo houses. In all these cases, the transport of concrete components (cement, gravel and sand) contributed the most.

Finally, the effects of the external environmental constraints were analysed. Each location had its own distinctive requirements for both earthquakes and wind loads as presented on **figure 4**.

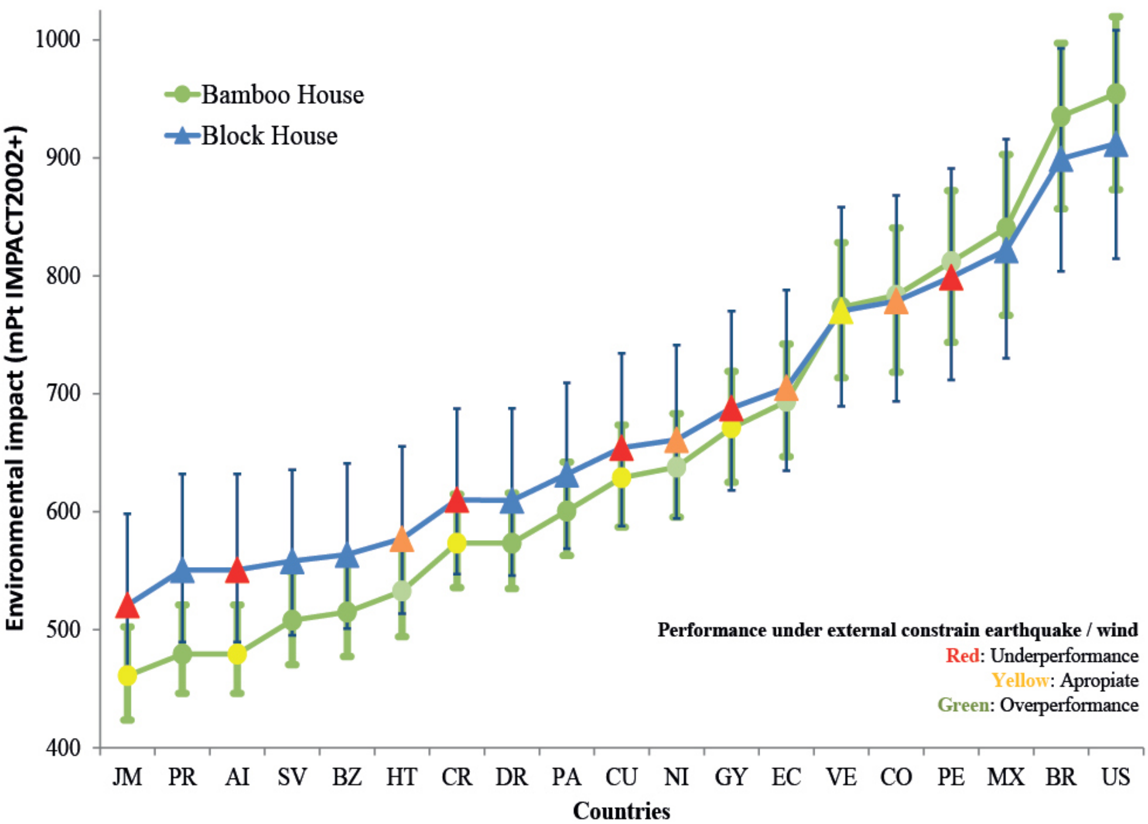

Figure 4. Environmental impact and technical performance

A colour gradient from red to green was used to identify the technical performance. Red indicates that a given house design would underperform for the seismic/wind demands on the location. Thus, a house might collapse under the expected external environmental constraints, and the structural design would need to be improved. Yellow represents an appropriate performance in which the house would withstand the external environmental constraints. Finally, green represents the over-performance of a house in a given location. This means that it would be possible to reduce the structural components for a given house design in that location and reduce its environmental impact. From **figure 4** it can be observed that the "bamboo house" often had the lowest environmental impact and a better structural performance. However, in some cases, its impact was much higher than that from the benchmark design, and it still had a better structural performance. This feature can support the decision-making process when choosing appropriate construction systems and house designs for specific locations; thus, a decision maker/designer can prioritise environmental impacts and structural performance depending on the local conditions.

Nansai et al. (2005) and Potting (2000) did extensive work on the regionalization of environment impacts on LCA which improved the quality of the results. In the case of LCA of buildings, uncertainties in data are the highest at the early stages of design, when most of the improvements can be achieved. The methodology here presented aims to generate a range in which the environmental impact can occur by considering the variability on production practices of construction materials. These kind of results are easier to produce at early stages of design and can therefore help decision makers and designers to make the optimal choices of construction materials. Furthermore, the work of (Mutel and Hellweg 2009; Nansai et al. 2005; Potting 2000) presented an approach in which both the LCIA and evaluation methods were regionalised to bridge the data gap. In the present research, the characterization process was conducted by including the country-specific electricity mix in the calculations and the performance range of technology. These characteristics were combined with the evaluation method IMPACT2002+ (Jolliet et al. 2003b), which can be considered global. Nevertheless, it is possible to further refine the model by including the regionalised evaluation methods and LCIA, as proposed by Mutel et al.

National transport distances were studied in detail in the present research, and several models were developed to represent four possible transport-distance ranges in relation to the country size. However, as proposed by (Fries and Hellweg 2014; Hellweg and Mila i Canals 2014), more detailed models are needed in which the effects of international transport can be better represented, to acknowledge the global characteristics of many construction materials used today. The contribution to variability was used to better understand the effect of the different construction materials on the LCA results and to test sensitivity, as proposed by (Azapagic et al. 2011). This approach proved to be very useful for bio-based construction materials, such as bamboo, and for construction materials whose production process is highly variable and uncertain. The uncertainties in the results were calculated using part of the methodology developed by (Hoxha et al. 2014); this approach provides an effective and fast assessment of the uncertainty in the data related to the environmental impacts. With further developments in the model, it would be possible to include factors such as replacement, maintenance and end of life.

4. Conclusions

This research presents a LCA methodology for buildings that account for the local variability of production on a global scale. The use of GIS enabled the development of characterized LCIA data for construction materials and buildings with a high degree of consistency. Moreover, the data produced represented the local context by considered country-specific transport distances and electricity mixes. Furthermore, the proposed approach was able to represent the range of production practices in use around the world. The results produced with the present methodology provide a range of values representing the possible variability of results. On the present research the highest level of uncertainty was used, considering that only the country and construction materials were known. If a practitioner has more detailed information and data the level of uncertainty and thus the variability of the results could be reduced. Finally, the proposed methodology can assess building designs in their early stages, when the uncertainty is highest; thus, it can identify potential improvements to each design and recognise the structural needs in specific locations.

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Compliance with Ethical Standards

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Figure Captions

Fig. 1 Conceptual framework of the methodology

Fig. 2 LCA of buildings, transport distance, and production efficiency

Fig. 3 Contribution to the environmental impact

Fig.4 LCA and structural performance

Tables

Table 1 Land area and transport distances from literature

Table 2 Potential transport distances (sample)

Table 3 Bill of construction materials used in five house designs